Black holes as observatories for beyond-standard model physics

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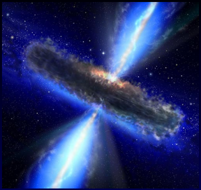
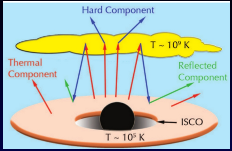
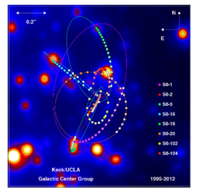
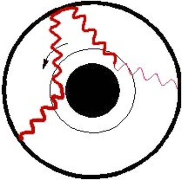
Gravitational Physics Seminar – Cardiff University, 25 April 2014





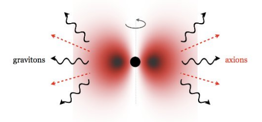


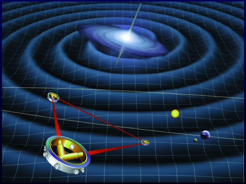


study fundamental fields

- dark matter candidates
- axions from string theory compactifications
- modified gravity, e.g., scalar – tensor theories

using precision black hole physics





Outline

1. **Introduction**
   - Superradiance and the "black-hole bomb"
   - Massive scalar fields in BH background
2. **Lighthouses in the sky – scalar clouds around black holes**
3. **Summary and Outlook**

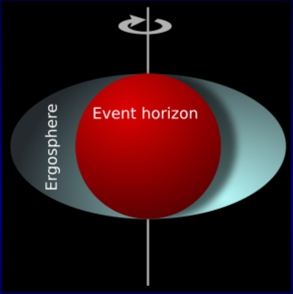
Superradiance

consider scattering of wave $\Phi \sim \exp(-\imath\omega t)$ off a Kerr BH with $(M, a/M)$

- negative energy and angular momentum flux into horizon for

$$0 \leq \omega_R < m\Omega_H = m\frac{a}{2Mr_+}$$

- decrease of the BH's mass and spin
- amplification of field's amplitude



$\Rightarrow$ "superradiant scattering" or "superradiance" (Zel'dovich '71; Misner '72; Press & Teukolsky '72-'74)

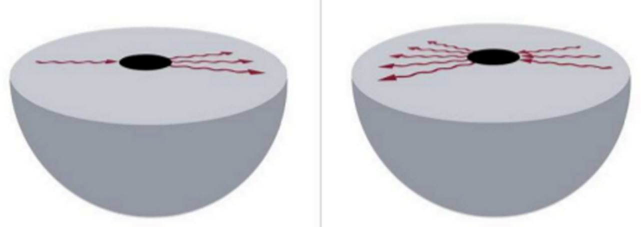
$\Rightarrow$ mechanism to extract energy and angular momentum from BH

- amplification factors for nearly extremal BHs and (Press & Teukolsky '72-'74)
  - spin-0 field: $\sim 0.04\%$
  - spin-1 field: $\sim 4\%$
  - spin-2 field: $\sim 138\%$

Superradiant instability

"Black hole bomb" mechanism (Zel'dovich '71, Press & Teukolsky '72, Cardoso et al '04, . . .)

- superradiant scattering of wave
  $\Rightarrow$ net amplification in one reflection and scattering
- confine system inside perfectly reflecting cavity
  $\Rightarrow$ exponentially growing modes
  $\Rightarrow$ "superradiant instability" or "Black hole bomb" (Press & Teukolsky '72)



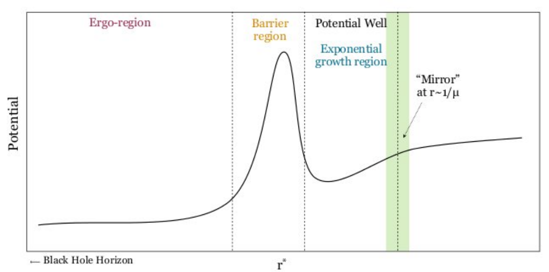
credit: A. Sousa

Superradiant instability

natural "mirror"

- asymptotically AdS: timelike boundary (Hawking & Reall '00, Cardoso & Dias '04, Cardoso et al '13, ...)
- massive fields with $m_B = \mu\hbar$; "mirror" if $\omega_R \lesssim \mu$

(Damour et al. '76, Detweiler '80, Zouros & Eardley '79, ...)



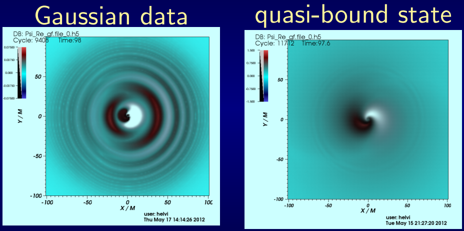
Arvanitaki & Dubovsky '11

Massive scalar fields – what do we know?

Klein-Gordon equation (in Kerr background)

$$(\Box - \mu^2)\Phi = 0\,, \quad \text{with} \quad \Phi = \exp(-\imath\omega t)\exp(\imath m\phi)S_{lm}(\theta)R_{lm}(r)$$

- solutions:
  - quasi-normal modes (radiative bcs)
  - quasi-bound states ("trapped" in potential well)
- decaying modes for $\omega_I < 0$; growing modes for $\omega_I > 0$



Gaussian data | quasi-bound state

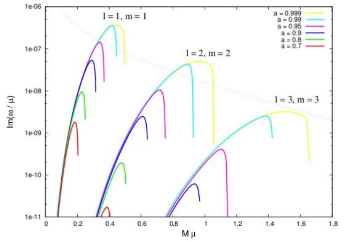
Witek et al '12

- for small couplings $M\mu \lesssim 0.1$: hydrogen-like spectrum (Detweiler '80, Dolan '07, Pani et al '12)

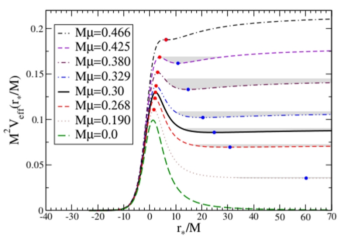
$$\omega_R \sim \mu\left[1 - \left(\frac{M\mu}{2(n+l+S+1)}\right)^2\right]$$

$\Rightarrow$ "gravitational atom"

Massive scalar fields - frequency domain



Dolan '07



Barranco et al '11

- instability is regulated by BH spin and mass coupling

$$\frac{r_+}{\lambda_C} \sim \frac{G}{c\hbar} M\mu = 7.45 \cdot 10^9 \left(\frac{M}{M_\odot}\right) \left(\frac{m_B}{(eV/c^2)}\right)$$

$\Rightarrow$ most effective for $M\mu \sim \mathcal{O}(1)$ and high spins

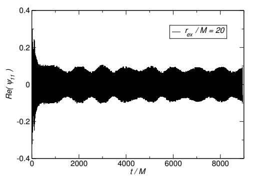
- maximum instability growth rate for bound states (Dolan '07, Cardoso & Yoshida '05)

$$l = m = 1\,,\ a/M = 0.99\,,\ M\mu = 0.42 : \tau = 1/\omega_I \sim 10^7\, GM/c^3 \sim 50\, (M/M_\odot)\, \mathrm{s}$$

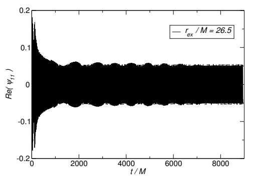
Massive scalar fields – time domain

- formulation of KG equation as time evolution problem (Witek et al '12, Dolan '12)
- initial data with $Y \sim Y_{1-1} - Y_{11}$, $M\mu = 0.42$, $a/M = 0.99$

$r_{\rm ex} < r_{\rm node}$



$r_{\rm ex} \sim r_{\rm node}$



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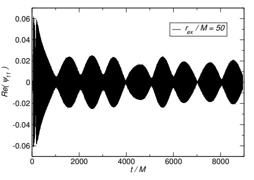
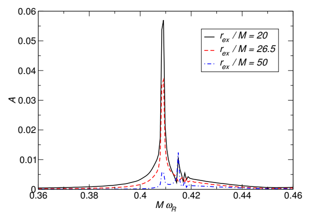


- beating between overtone modes
  $\omega_{R,1} = \omega_{R,0} + \delta_{10}$, $\delta_{10} \ll 1$

  $\psi \sim (A_0 - A_1)\sin(\omega_{R,0}t) + A_1 \sin(\omega_{R,0}t)\cos(\delta_{10}/2t)$
- generic feature in BH backgrounds

(Dolan '12; Witek et al '12; Degollado & Herdeiro '13)



(Witek et al '12)

Superradiant instability in physical systems

- for astrophysical BHs ($3M_\odot \lesssim M \lesssim 10^9 M_\odot$) and SM particles: $M\mu \sim 10^{18}$

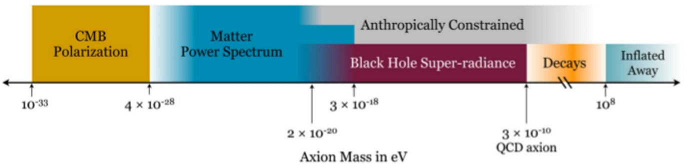
$$\tau \sim 10^7 \exp(1.84 M\mu) \left(\frac{GM}{c^3}\right)$$ (Zouros & Eardley '79)

  $\Rightarrow$ irrelevant???
- candidates:
  - QCD axion with $m_B \sim 10^{-10} eV \left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)$ (Peccei & Quinn '77)
  - ultra-light bosons emerging in string theory compactification

    $\Rightarrow$ "string axiverse" – plethora of ultra-light axion-like particles

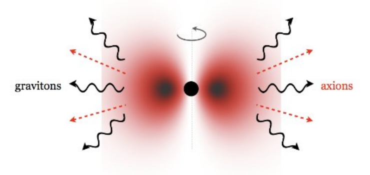
    (Arvanitaki & Dubovsky '10, '11, Kodama & Yoshino '11)

    $\Rightarrow$ bosonic clouds around BHs if $10^{-21} eV \leq m_B \leq 10^{-8} eV$
  - fundamental fields, e.g., in extensions of GR with axionic or dilaton coupling



Arvanitaki & Dubovsky '10

Signatures of the superradiant instability



(Arvanitaki & Dubovsky '11)

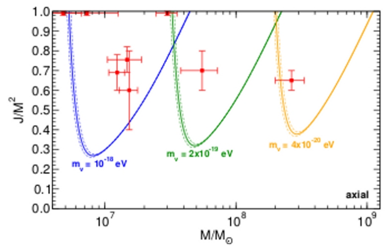
- formation of bound states around BHs
  $\Rightarrow$ "gravitational atom"
- scalar and modified gravitational wave emission

- accretion vs. amplification

↙ ↘

"gravitational wave pulsar"
$\Rightarrow$ long-lived scalar & gravitational signals

gaps in Regge plot
$\Rightarrow$ constraints on field's mass



Pani et al '12

- estimates for BH spin and mass from electromagnetic observations

(McClintock & Remillard '09, Reynolds '13, Ferrarese et al '04, Denney et al '10, Brennemann et al '11,. . .)

$\Rightarrow$ study beyond-SM physics by precision BH physics

What has been done?

- massive scalar fields around BHs (Damour et al '76; Zouros & Eardley '79; Detweiler '80; Furuhashi '04; Cardoso & Yoshida '05; Dolan '07; Berti et al '09; Konoplya et al '06; Pani et al '12; Hod '12; Barranco et al '13; Strafuss & Khanna '05; Kodama & Yoshino '12; Barranco et al '12, '13; Dolan '12; Witek et al '12; . . .)
- Proca fields around BHs (Rosa & Dolan '11; Pani et al '12; Witek et al '12)
- massive gravity: $M\omega_I \sim \mathcal{O}(1)$, monopole & superradiant instability (Brito et al '13, Babichev & Fabbri '13)
- BHs surrounded by matter in scalar-tensor theories
  $\Rightarrow$ scalar fields gain effective mass (Cardoso et al '13)
- charged scalar in Reissner-Nordström backgrounds (Degollado & Herdeiro '13; Degollado, Herdeiro & Rúnarsson '13; Hod '13, Degollado & Herdeiro '13)
- non-linear self-interaction $\Rightarrow$ "bosenova"-like particle bursts (Yoshino & Kodama '12, '13)
- non-linear evolutions of the massive scalar field – BH system (Okawa et al '14)
- non-linear studies of superradiance for gravitational waves (East et al '13)

Scalar clouds around black holes – non-linear evolutions

(H. Okawa, HW, V. Cardoso, 1401.1548)

- in dynamical regime – final state?
- formation of "gravitational atom"?
- "gravitational wave pulsars"?

$\Rightarrow$ include backreaction onto spacetime

What is the fate of the system?

- consider full, non-linear GR – Klein-Gordon system in $D = 4$

$$
\begin{aligned}
{}^{(4)}R_{\mu\nu} - \frac{1}{2} g_{\mu\nu}\, {}^{(4)}R =& -4\pi \left[g_{\mu\nu} \left(\partial_\lambda \Phi^* \partial^\lambda \Phi + \mu_S^2 \Phi^* \Phi \right) - 2 \partial_{(\mu} \Phi^* \partial_{\nu)} \Phi \right] \,, \\
(\Box - \mu_S^2) \Phi =& 0
\end{aligned}
$$

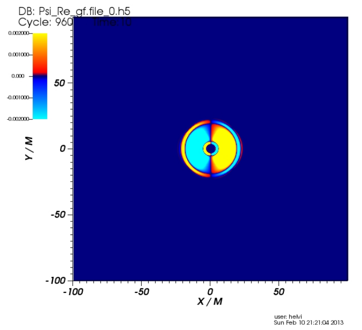
- strategy: non-linear time evolutions in $3 + 1$ using NumRel techniques
- two independent codes: COSMOS and LEAN-SR (based on CACTUS / CARPET and Sperhake '06)

Cosmos cluster @ DAMTP/CMS

- solve constraints → initial data:
    - analytic ID for Schwarzschild + Gaussian scalar
    - numerical ID for Kerr + Gaussian or bound state scalar
- evolution equations:
    - BSSN formulation + puncture gauge
- wave extraction:
    - Newman-Penrose formalism for GWs

Scalar clouds around BHs – Setup

1. Schwarzschild BH and scalar field with $\mu = 0.42$
   initialize scalar field as Gaussian wave packet
   $\Pi_0 \sim \exp\left(-\frac{(r-r_0)^2}{w^2}\right) \sum_{lm} Y_{lm}(\theta,\varphi)$
2. Kerr BH with $a_0/M_0 = 0.95$ and scalar field with $\mu = 0.30$
   initialize scalar field as Gaussian or pseudo-bound state

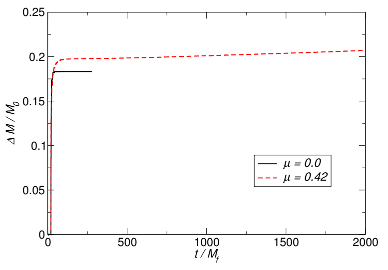


Evolution of a scalar field with $\mu = 0.42$, $r_0 = 12M_0$, $w = 0.5M_0$, $Y = Y_{1-1} - Y_{11}$ around Schwarzschild

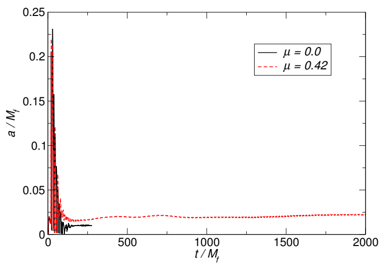
Scalar cloud around Schwarzschild – Results

scalar field with $r_0 = 12M_0$, $w = 0.5M_0$, $Y = Y_{1-1} - Y_{11}$, $\mu = 0.42$

relative BH mass



spin a/M

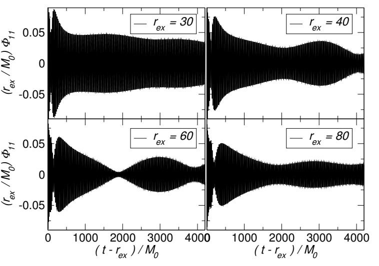


- increase in BH mass
- $\mu = 0.0$: $\Delta M/M_0 = 18.3\%$
- $\mu = 0.42$: $\Delta M/M_0 = 20.9\%$ (after $t \sim 2000M$)

- $\mu = 0.0$: $a/M \sim 0.01$
  $\mu = 0.42$: $a/M \sim 0.025$
- settles down to Kerr BH with larger mass and small spin

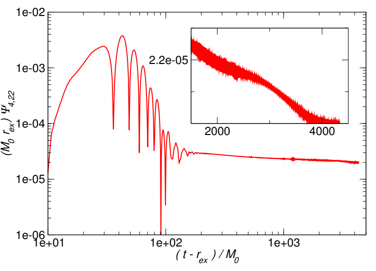
Scalar cloud around Schwarzschild – Results

scalar field Φ_{11}



- beating between overtone modes
- space dependent excitation of modes
- qualitative agreement with linear evolutions (Dolan '12, Witek et al '12)

gravitational wave $\Psi_{4,22}$

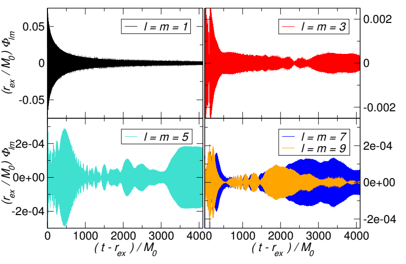


- quasi-normal ringdown
  $M\omega_{22} = 0.371 - \imath 0.084$
- long-lived GW emission
  $M\omega^{\Psi_4}_{R,22} \sim 0.823 \sim 2M\omega^{\Phi}_{R,11}$
  $\Rightarrow f \sim 35kHz\,(M/M_{\odot})^{-1}$
- beating pattern, induced by scalar field

Scalar cloud around Schwarzschild – Results

- excitation of higher multipoles
- remember: initial data is Gaussian scalar $\sim Y_{11} - Y_{1-1}$ around Schwarzschild

scalar field Φ_{lm}



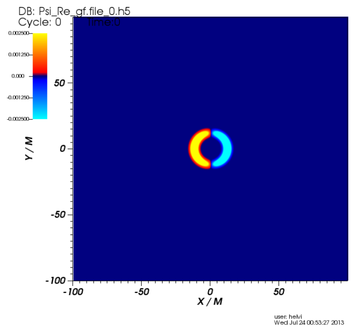
- possible explanations:
  - non-linear effects?
  - shift to shorter length scales $\Rightarrow$ indication for gravitational turbulence? (Okawa et al '13, Yang et al '14)
  - remember: gravitational turbulence found in AdS spacetimes

    (Bizon & Rostworowski '11, Maliborski '12, Buchel et al '13, Adams et al '13)

$\Rightarrow$ more work needed!

Scalar clouds around Kerr – Results

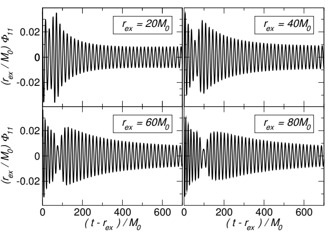
Evolution of a pseudo-bound state scalar field with
$\mu = 0.35$, $r_0 = 12M_0$, $w = 2M_0$ around Kerr with $a_0/M_0 = 0.95$



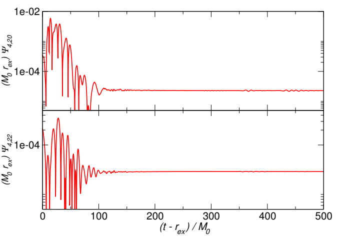
Scalar cloud around Kerr – Results

emission of scalar and gravitational waves

scalar field Φ_{11}



gravitational wave Ψ_4



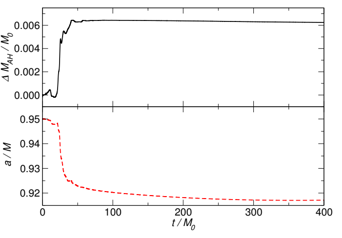
- long-lived bound states
- beating effect
- frame-dragging effects
- before interaction: $\omega_R \sim 0.352 < m\Omega_H$
  after interaction: $\omega_R \sim 0.341 > m\Omega_H$

- excitation of ringdown signal
- long-lived gravitational wave emission with
  $M\omega_{R,22} \sim 0.65$
  $\Rightarrow f \sim 20kHz\,(M/M_\odot)^{-1}$

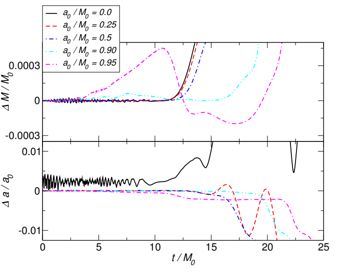
Scalar cloud around Kerr – Results

response of black hole

long time behaviour:



at early times:



- overall increase in mass $\Delta M/M_0 \sim 0.6\%$
- decrease in spin to $a/M \sim 0.917$
- here: accretion dominant $\Rightarrow$ shift in Regge plane towards larger mass and smaller spin

- small initial spin: increase in mass, decrease in spin $\Rightarrow$ accretion
- high initial spin: simultaneous decrease in mass and spin $\Rightarrow$ hint for superradiant response
- compatible with induced gravitational superradiance

Summary

- superradiance – mechanism to extract BH energy and angular momentum
- here: "BH bomb" mechanism triggered by ultra-light massive fields
- observation of astrophysical BHs
  $\Rightarrow$ constraints on allowed field mass
- first full non-linear investigations of massive scalars surrounding BHs
  - Schwarzschild
    - at late time: Kerr BH with larger mass and small spin
    - formation of scalar cloud and long-lived gravitational radiation
  - Kerr
    - hint for superradiance effect
    - at late times: Kerr BH with larger mass and smaller spin
    - long-lived quasi-bound states and gravitational wave emission
    - frame-dragging effects
  - long-lived scalar and gravitational radiation with $f \sim \mathcal{O}(10) kHz (M/M_{\odot})^{-1}$
    $\Rightarrow$ potentially observable with advLIGO or eLISA

What comes next?

- for scalars: too long time-scales ($\tau/M \sim 10^7$) for definite statements
- higher amplification factor for spin-1 / spin-2 fields
  $\Rightarrow$ extension to different fields, space dependent mass coupling, ...
- framework adaptable to multiple scalars and / or BH binaries
- modification in presence of accretion discs? suppression of instable modes?
- understanding of gravitational turbulence in asymptotically flat spacetimes

Thank you!

animations available @ http://blackholes.ist.utl.pt